THERMAL CONTROL DESIGN OF THE GALAXY EVOLUTION EXPLORER

Siu-Chun Lee*
Applied Sciences Laboratory, Inc.
Hacienda Heights, CA

Glenn Tsuyuki†
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA

ABSTRACT

This paper describes the thermal control design of GALEX, an ultraviolet telescope that investigates the UV properties of local galaxies, history of star formation, and global causes of star formation and evolution. The telescope consists of a primary mirror for collecting light into the second mirror, which in turn focuses light onto the detectors located inside a focal plane assembly. In addition to the typical thermal requirements for hardware within the instruments, the spatial temperature variation within the primary and secondary mirrors must be kept within 1°C. The GALEX thermal design utilizes appropriate surface coatings, multi-layer insulation blanket, radiators, heaters, and thermostats. A detailed analytical model that accurately represented the GALEX mechanical configuration was constructed by utilizing SINDA/3D. Radiation exchange factors and environmental absorbed fluxes were calculated by using TSS. The thermal design analyses considered extreme, but realistic environmental parameters in conjunction with flight mission parameters to predict the maximum and minimum temperatures for the optical components and all electronic equipment. Details of the GALEX thermal design are discussed in this paper.

INTRODUCTION

Galaxy Evolution Explorer (GALEX) is a space-imaging telescope that investigates the ultraviolet (1350-3000 Å) properties of local galaxies and maps the history of star formation. It is scheduled to launch on a 3-axis stabilized spacecraft on September 2001 by utilizing the Pegasus XL into a 690-km circular orbit with an orbit plane inclination of 28.5°.

Figure 1 shows a schematic diagram of GALEX, which consists of the telescope assembly (TA) and an instrument compartment. Figure 2 depicts the flight spare TA. The TA is a Ritchey-Chrétien type Cassegrain system consisting of a 50-cm

---

* Senior Member, President
† Senior Member, Program Element Manager

primary mirror (M1) with central hole, a 25-cm secondary mirror (M2), central metering tower that supports the M2 assembly, primary mirror baffle, M2 baffle, mirror mounts, mirror coatings, and structural interface hardware to mount the TA to the rest of the instrument. Light is focussed into the detectors that are mounted inside the Back Focal plane Assembly (BFA) in the instrument compartment. Spectral selectivity is performed by either the Grism or Imaging window, both of which are mounted on a filter wheel inside a housing immediately below M1. The Grism and Imaging window are alternately rotated into the light path for spectral selection by a mini-dual drive actuator motor.

The M2 is bonded to a hub that is mounted on a spider structure and a series of concentric light baffles, all of which are enclosed by a shroud. The entire M2 assembly is secured on three struts that are attached to the inner baffle and the lower hub to which M1 is bonded. Three pairs of struts at the M1 hub support the TA on the telescope support plate (TSP). The TSP is supported off the instrument deck by three cylindrical bipods. The compartment in between the TSP and the instrument deck houses the electronic equipment and the BFA which contains the Far- and Near- ultra-violet (FUV & NUV, respectively) detectors. The instrument compartment is enclosed by multi-layer insulation (MLI) on all sides.

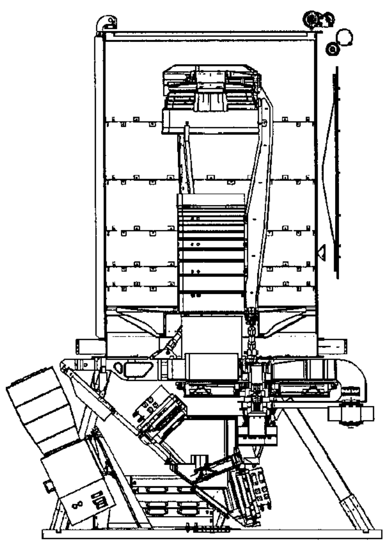

Figure 1 - GALEX instrument mechanical configuration

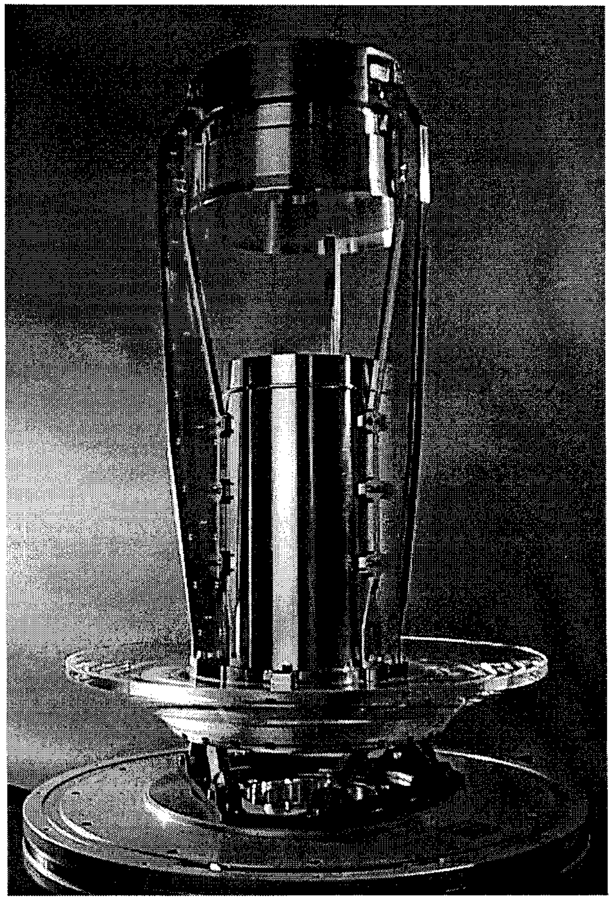

Figure 2 - TA flight spare prior to application of thermal surface finishes

Athermalization of the BFA is achieved by utilizing a truss system attached to the TSP. A star tracker is mounted on the instrument deck outside of the MLI tent.

A thermal control design that complies with all thermal requirements has been achieved by utilizing heaters, thermostats, radiators, MLI, and surface finishes. The thermal design was based on the consideration of extreme, but realistic environmental parameters and spacecraft orientations that are consistent with flight attitude constraints. The thermal design also provides the capability to

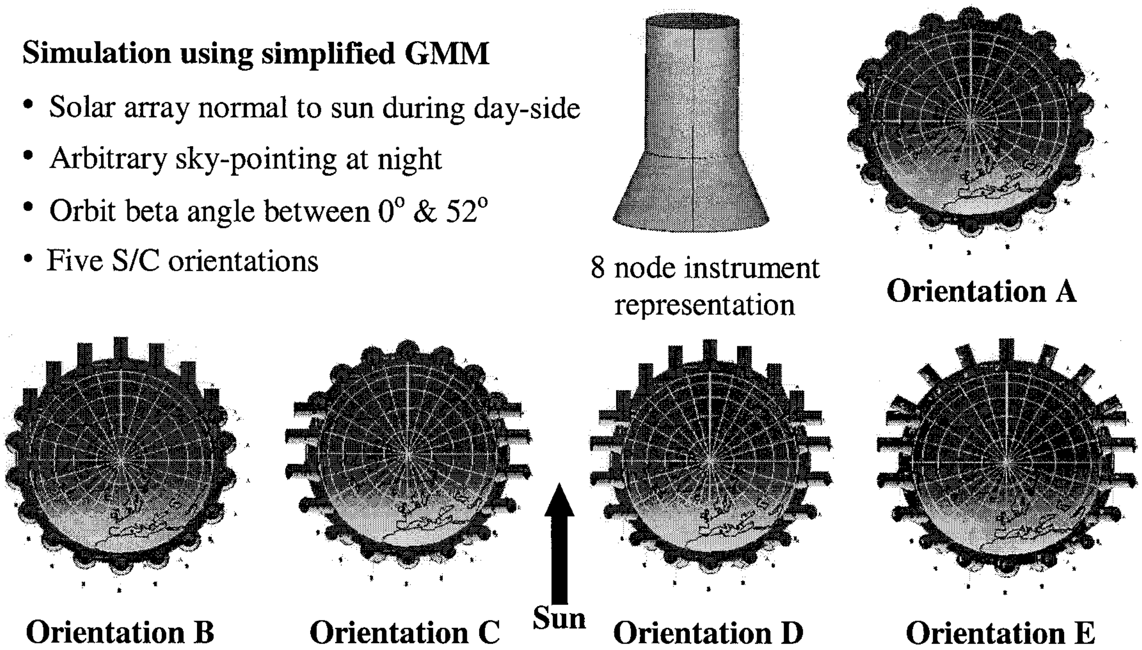

Figure 3 - Spacecraft attitude & orientation for assessing worst-case condition

compensate defocus by heating the spacer in the M2 assembly. In the survival mode GALEX is maintained within the non-operating allowable flight temperature (AFT) limits by utilizing heaters controlled by thermostats that are placed at strategic locations.

THERMAL CONTROL DESIGN

Thermal Requirements

The electronic equipment and optical components of the GALEX instrument must be maintained within their specified operating and non-operating AFT limits during the science and safe modes, respectively. During the operating mode, all the electronics are powered and GALEX performs all sky survey at night. The electronic equipment include the Digital Processor Unit (DPU), the Front End Electronics (FEE) and the High Voltage Power Supply (HVPS), whose AFT limits are 0 and 40°C, and the AFT limits for NUV/FUV detectors are -15 and +35°C. The AFT limits for the optical components are –15 and 25°C. In addition, the AFT limit of -15°C for the Grism and Imaging window of applies only during the day when the telescope is not taking science data. They must be maintained above -5°C during science data taking at night. The most stringent requirement is the <1°C spatial temperature variation of M1 and M2. The non-operating conditions include the decontamination and safe modes, during which the electronic equipment is mostly powered off. The non-operating AFT limits

Table 1 - Thermal environment parameters

	Worst Cold	Nominal	Worst Hot
Solar Constant (W/m^2)	1287	1367.5	1420
Earth Albedo	0.2	0.3	0.4
Earth Emission (W/m^2)	189	241	260

Figure 4 - Thermal block diagram

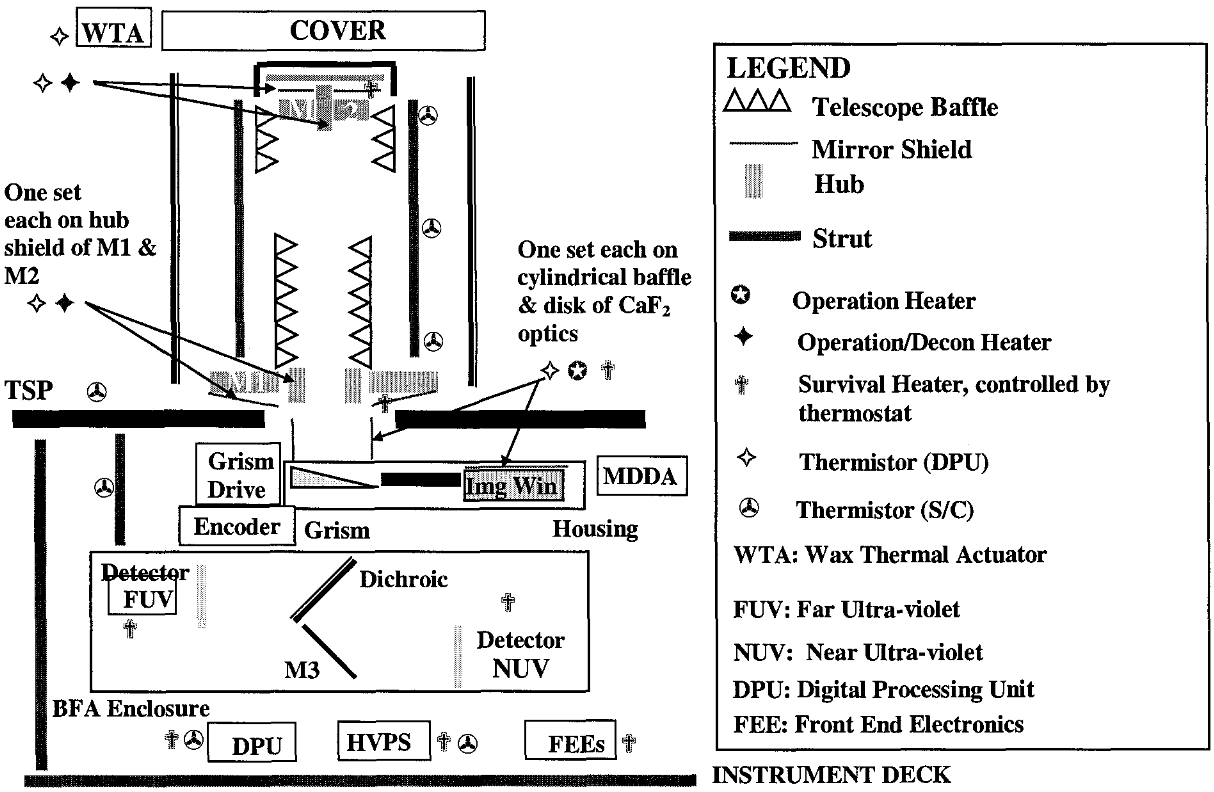

Table 2 - Instrument average power dissipation

Component	Operating Instrument Power (Watts) Day Min/Max	Night Min/Max
DPU	24.2/30.0	28.8/34.5
FUV/NUV FEEs	29.6	29.6
FUV/NUV HVPSs	2.4	2.4
FUV Detector	2.1	2.1
NUV Detector	2.1	2.1
Total	60.4/66.2	65.0/70.7

are generally 10 °C beyond the operating AFT limits.

Thermal Environment

GALEX will be launched on September 2001 into a 690-km circular orbit with a 28.5° orbit plan inclination. It is a 29-month mission, with the telescope performing all-sky survey and deep surveys at night. The range of thermal beta angles is expected to be ±52°. The environmental flux parameters used in thermal analyses, as summarized in Table 1, are specified according to standard thermal design practice by stacking extreme values for the cold and hot design conditions, respectively.

In order to determine the conditions for the extreme hot and cold cases, a simplified geometric model of GALEX as shown in Figure 3 was constructed for calculating the absorbed environmental fluxes for the extreme thermal beta angles of 0° and 52°. The orientation of GALEX in flight is subjected to two attitude constraints: (1) the solar panel is sun-tracking during daytime, and (2) the telescope can be in any sky-pointing orientation at night. Five most probable orientations, as depicted in Figure 3, were identified. As shown in the figure, the solar vector lies in the XY plane of the GALEX instrument coordinate system during daytime for Orientations A and B. For Orientations C, D, and E, GALEX rotates about the X-axis as it comes out of eclipse and goes through a full 180° rotation in entering eclipse. The orientations during eclipse are self-evident in the figure. Based on the evaluation of the absorbed flux by each surface of this simplified geometric model, the extreme hot condition was determined to be Orientation B and β=52°, whereas the extreme cold condition was Orientation E and β=0°.

To ensure a conservative thermal control design, the hot spacecraft attitude and maximum power are used for the hot design condition, and the cold spacecraft attitude and minimum power are used for the cold design condition. The DPU and FEE are the highest power dissipation equipment, which dissipate 30W and 76W, respectively. The total heat dissipation of GALEX is about 112W. The equipment power dissipations are shown in Table 2. Cold conditions are used to size heaters for the operational, decontamination, and survival modes, while the radiators are sized based on hot conditions.

Thermal Design

The thermal design of GALEX utilizes both passive and active thermal control methods that include surface coatings, MLI, radiator, thermal shield, heaters, and thermostats. Heaters are used to maintain the Grism and Imaging window above –5°C for science data acquisition. They are also applied on the M1 and M2 assemblies to minimize their spatial temperature variation, to provide defocus compensation ability, and to raise M1 and M2 to the decontamination levels. Figure 4 shows the thermal control design block diagram of GALEX, which depicts the locations of the operational and

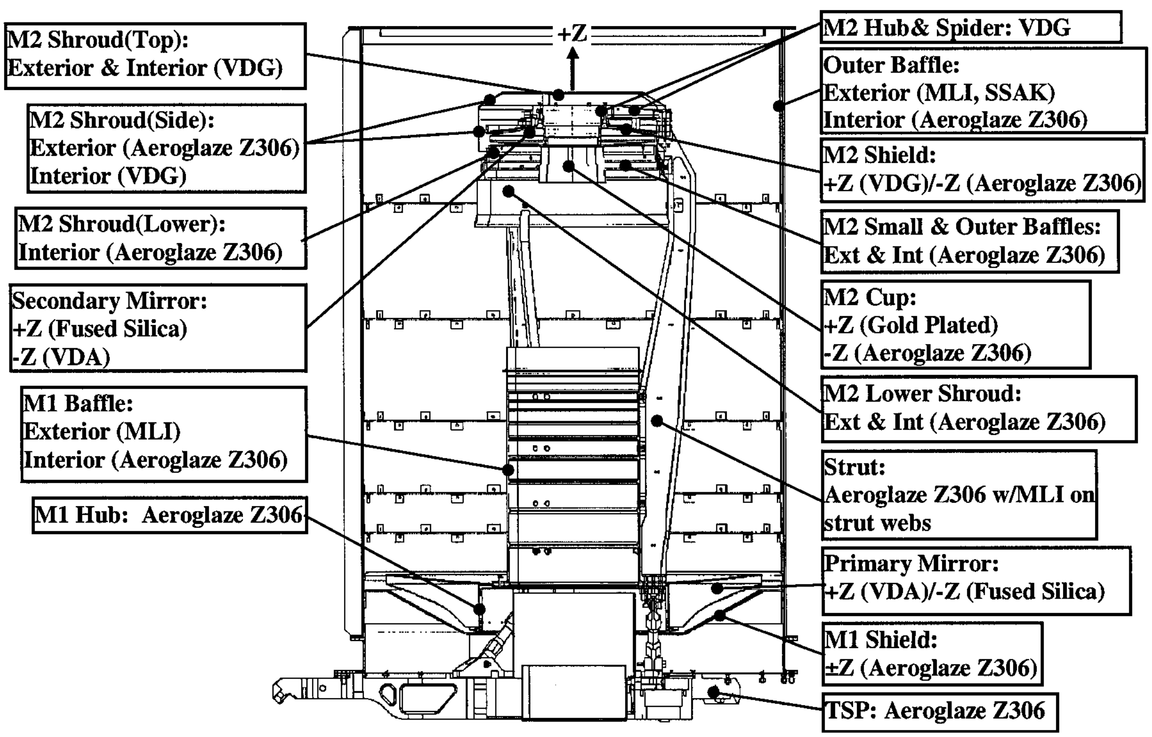

Figure 5 - Telescope assembly thermal surface finishes

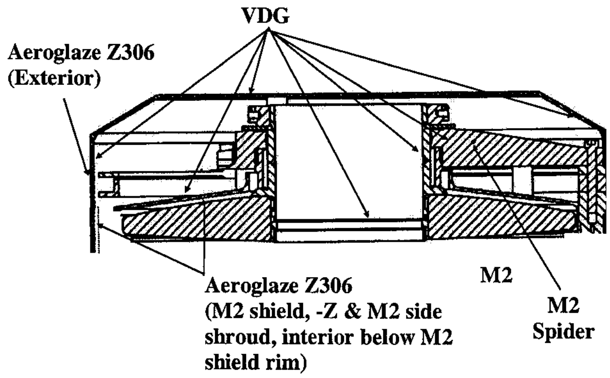

Figure 6 - Detailed view of M2 surface

replacement heaters, thermostats, and thermistors.

The outer barrel of the TA is wrapped with MLI to minimize the influence of the environment. Because elimination of stray light is of paramount importance to telescope performance, MLI with black beta cloth outer layer, black paint coated baffle fitted inside the M1 hub, and black coating (Z306) on all surfaces along the optical path are applied to minimize stray light reaching the detectors. The web of each support strut and the M1 baffle are covered with MLI with a black beta cloth outer layer to reduce the non-linearity of temperature distribution along the strut. A summary of the thermal control finishes in the TA is given in Figure 5.

Because the M2 assembly is located at the top of the TA, the M2 shroud has a full view of deep space and can become very cold. An appropriate combination of surface finishes including both high and low emissivities are needed to minimize heater power usage and maintain the spatial temperature difference of M2 to within 1°C. This is achieved by applying the surface finishes as depicted in Figure 6. As shown, the +Z side of the shroud, the interior surfaces of the M2 assembly, and the +Z side of the M2 thermal shield are all gold coated in order to reduce heat loss to space. On the cylindrical side of the shroud, the external surface and the lower patch of the interior surface up to the upper edge of the mirror are painted black to enhance heat rejection by the mirror in the radial direction. This pattern of surface finishes enhances the uniformity of the temperature distribution inside the mirror.

Heaters are applied during normal operating conditions to maintain M1 and M2 above their cold AFT limits and for raising the mirrors to 50°C in the decontamination mode. The M1 thermal shield is shaped like an inverted cone underneath M1, and the M2 thermal shield is a disk situated on top of M2. The M1 shield is thermally isolated from the TSP and outer barrel by low thermal conductivity supports made of Vespel. Both sides of the M1 thermal shield are black anodized to enhance thermal coupling with the mirror and TSP.

The TSP is the major structure that separates the TA from the equipment compartment below. Attached to the under side of the TSP is the filter wheel housing in which the Grism and Imaging window are located. They are mounted diametrically apart on a wheel that rotates either one into the optical path and are heated by thermal shields with bonded heaters to –5°C. A cylindrical baffle supported on the TSP is used to heat the optics element in the optical path, and a disk attached to the bottom of the TSP/C-Clamp structure is used to heat the other element. The size and shape of the baffle and disk are optimized to minimize heater power usage.

To provide a stable temperature environment for the electronic equipment, the instrument compartment is enclosed by MLI to minimize heat loss to space. The MLI tent excludes the star tracker whose thermal design is provided by the spacecraft contractor. The surfaces of all equipment inside the compartment are black anodized to enhance

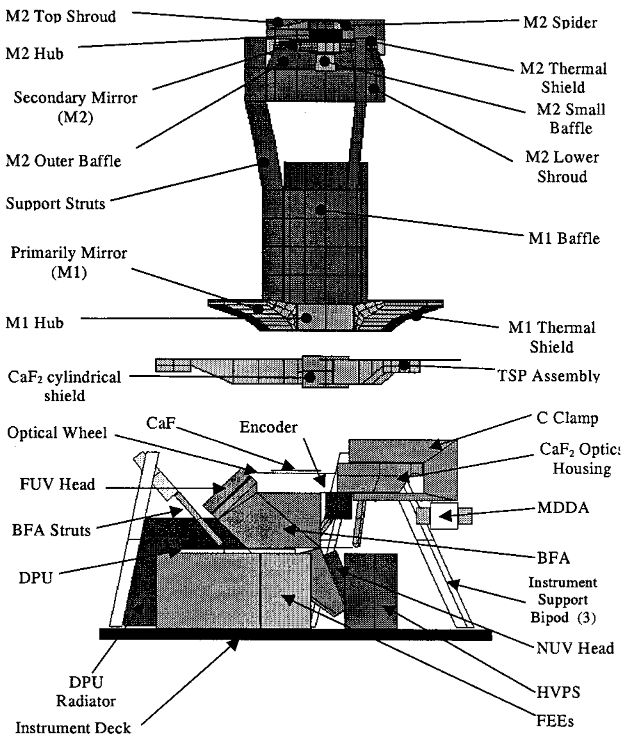

Figure 7 - Instrument thermal-geometric model

radiation heat exchange between the equipment. Aeroglaze Z306 is applied to the interior surfaces of the BFA as dictated by optical requirement. Dedicated radiators are attached to the DPU and FEE for heat rejection to space. Each radiator is configured like a picture frame around one side of the box that is exposed to space. This design reduces the size and weight of the radiators. The instrument deck is thermally isolated from the spacecraft by a MLI blanket.

Thermal Modeling

A detailed thermal-geometric model (TGM) of GALEX was constructed by utilizing SINDA/3D[1]. A thermal math model (TMM) that includes primarily the conduction network is generated from the TGM. The geometric math model (GMM) is also generated from the TGM in TRASYS format. This GMM is then imported into the Thermal Synthesizer System (TSS)[2] for calculating inter-nodal radiation interchange factors (RADKs) and environmental absorbed heat fluxes. The temperature predictions are mapped onto the TGM to facilitate assessment of the thermal design. Transient results are also animated to reveal the orbital temperature variation of various components.

Because of optical performance requirements, thermal distortion analyses must be performed as part of an end-to-end analytic verification. To support the thermal stress analyses, detailed temperature distributions of the structure and the various subsystems are needed. These include the support struts, the TA, TSP, and BFA, which have been modeled as accurately as practical. The TSP and BFA are each represented by a thermal network of over 250 nodes in order to obtain accurate temperature distributions. The M1 and M2 are each modeled by a thermal network of more than 200 nodes to ensure an accurate assessment of their spatial temperature variation. The electronic equipment, which include the DPU, FEE, HVPS, FUV and NUV detectors, are modeled with fidelity consistent with system level thermal modeling as six-sided boxes with an internal node. Optical components, which include the Grism, Imaging window, fold-mirror, beam-splitter, and the NUV and FUV windows, are each modeled as two-dimensional plate elements with 4 or more nodes. The bipods that support the TSP from the instrument deck and the struts with which the BFA is mounted on the TSP are modeled as rectangular plate elements with the equivalent surface area. The BFA struts are modeled strictly for the benefit of producing temperatures for use in thermal distortion analyses. Figure 7 shows the TGM cut-away views of the TA and instrument compartment of GALEX.

Pertinent information of the TGM such as the dimension and the thermal and optical properties of all nodes and surfaces are contained in the geometric data file. Upon

Table 3 - Operational Orbit-Average Analysis Results, °C

	M2 @ -15°C		M2 @ 0°C		M2 @ +15°C		Op AFT Limit, °C
	Cold	**Hot**	**Cold**	**Hot**	**Cold**	**Hot**	
M1	-13.9±0.5	1.0±0.4	-13.6±0.5	1.3±0.4	-13.3±0.5	1.6±0.4	-15 / +25
M2	-14.3±0.2	-15.1±0.0	0.5±0.3	0.2±0.1	14.0±0.3	14.6±0.4	-15 / +25
Grsim Win	-4.4±0.3	13.6±0.3	-4.2±0.3	13.8±0.3	-4.0±0.3	14.0±0.3	-15 / +25
IMG Win	-4.4±0.3	14.3±0.3	-4.2±0.3	15.0±0.2	-4.0±0.3	15.2±0.2	-15 / +25
MDDA	-8.6±0.1	13.7±0.2	-8.3±0.1	13.9±0.2	-8.1±0.1	14.1±0.2	-25 / +50
Grism Encoder	-1.8±0.1	20.3±0.2	-1.6±0.1	20.5±0.2	-1.5±0.1	20.6±0.2	-25 / +50
DPU	5.66	29.4	5.8	29.5	5.9	29.6	0 / +40
FEEs	8.56	28.7	8.7	28.8	8.8	28.9	0 / +40
HVPSs	4.63	26.3	4.8	26.4	4.9	26.6	0 / +40
NUV Detector	2.74	24.4	2.9	24.6	3.0	24.7	0 / +30
FUV Detector	2.28	23.4	2.4	23.5	2.6	23.7	0 / +30
NUV Win	1.8±0.1	23.4±0.1	2.0±0.1	23.5±0.1	2.1±0.1	23.6±0.1	0 / +30
FUV Win	1.5±.0.0	22.8±0.0	1.7±0.0	22.9±0.0	1.8±0.0	23.0±0.0	0 / +30
Fold Mirror	1.7±0.1	23.2±0.1	1.8±0.1	23.4±0.1	2.0±0.1	23.5±0.1	-15 / +25
Splitter	1.0±0.1	22.5±0.1	1.2±0.1	22.6±0.1	1.3±0.1	22.7±0.1	-15 / +25

completion of the TGM, a GMM in the TRASYS format is generated from SINDA/3D, which is then, imported into TSS for the calculation RADKs and environmental absorbed fluxes. The calculated RADKS and heat fluxes are then incorporated into the SINDA/3D thermal model. The TGM contains about 2100 nodes and 1600 surfaces.

THERMAL ANALYSIS

Extensive thermal analyses have been performed to develop a thermal control design that meets all of the temperature requirements for the operating and non-operating modes. Pertinent aspects for these modes are summarized below:

(1). Operating mode. The operating mode assumes that all electronics are in their normal operating conditions. The thermal control design is developed to accommodate both the extreme hot and cold thermal environments.

(2). Decontamination mode. M1 and M2 are heated to 50°C by enabling the decontamination heaters. All equipment except the DPU are turned off, which provides close-loop thermal control via thermostats located on the M1 and M2 shields and the M2 hub. To ensure conservative sizing of the heaters, the orbit beta angle, environmental constants, and spacecraft attitude for the extreme cold condition are applied in the thermal analyses.

(3). Survival mode. All equipment are powered off in this mode. Replacement heaters powered by the spacecraft survival bus are enabled to maintain all optics and electronic equipment above their minimum non-operating temperature limits. Survival heaters are sized based on the beta angle, environmental constants, and spacecraft attitude for the extreme cold condition for conservatism.

Table 4 – Non-Operational & Decontamination Orbit-Average Analysis Results, °C

	Decontamination[1]	Non-operation Cold	Non-operation Hot	Non-Op AFT Limit, °C
M1	45.3±4.0	11.8±2.0	-16.6±2.2	-20 / +35
M2	48.7±0.6	9.6±1.2	-17.2±1.6	-20 / +35
Grsim Win	9.7 ±0.6	14.0±0.1	-14.0±0.2	-15 / +40
IMG Win	6.9±0.2	14.6±0.2	-14.0±0.1	-15 / +40
MDDA	2.9±0.1	12.7±0.1	-16.7±0.1	-45 / +55
Grism Encoder	8.0±0.1	16.3±0.1	-10.9±0.1	-45 / +55
DPU	6.4	15.7	-9.1	-10 / +40
FEEs	-9.2	15.7	-9.1	-10 / +50
HVPSs	-3.0	17.9	-8.8	-10 / +50
NUV Detector	1.4	21.0	-4.5	-5 / +35
FUV Detector	1.9	21.1	-4.2	-5 / +35
NUV Win	1.5±0.0	19.4±0.1	-6.1±0.1	-20 / +35
FUV Win	1.8±0.0	19.4±0.0	-5.9±0.0	-20 / +35
Fold Mirror	1.5±0.0	19.2±0.2	-6.3±0.1	-15 / +40
Splitter	2.0±0.1	18.7±0.1	-7.0±0.1	-15 / +40

[1] Non-op AFT limits apply for decontamination, except for M1 & M2 max AFT which is 45±5°C

Trade studies were conducted systematically to evaluate the influence of the operational and replacement heaters, radiators, orbital environment, beta angle, and spacecraft orientation. These include both analyses utilizing orbit average environment and power dissipation and transient analyses that account for temporal characteristics of thermostat operations. Orbit average temperature predictions are summarized in Tables 3 and 4, in which the "±" sign indicates spatial variation. Heater power usage is summarized in Table 5.

A thermal control design that meets all of the thermal requirements has been successfully developed for GALEX. The thermal design utilizes appropriate surface finish, heaters, thermostats, and radiators. One set of heaters each for M1 and M2 serves both the operational and decontamination modes, since the decontamination heater is larger than the operational heaters. Because the FEE is powered off in both the decontamination and survival modes, a set of thermostat-controlled heaters powered by the survival bus is used for both operating and non-operating conditions. The operational heaters are controlled by the DPU, which provides close-loop quasi-proportional control by sensing the temperatures of the M1 and M2 shields and hubs.

In the hot and cold operational modes the temperature set points for all optical components except the M2 shield and hub remain unchanged under all conditions. The set points for M2 shield and hub are changed only for increasing the temperature of M2. A control band of 1°C is required to minimize the spatial temperature variation in M1 and M2. Since the DPU data count is calibrated at 12 bits over the temperature range of –50 to +150°C, this gives a theoretical resolution of 0.05°C per count. This provides sufficient resolution to accommodate the 1°C dead band in the temperature set points.

Table 5 - Heater power usage assuming 100% duty cycle

Component	Operational Heater (W)	Non-Operational Heater (W)	Decontamination Heater (W)
M1 Shield	5.0	12.5	37.5
M1 Hub	2.5	N/R	18.8
M2 Shield	0.7	0.9	0.9
M2 Hub	1.2	N/R	1.7
Grism	2.7	1.0	N/R
IMG Win	0.4	0.2	N/R
FUV Detector	N/R	3.8	N/R
NUV Detector	N/R	3.8	N/R
DPU	N/R	16.5	N/R
FEEs	N/R	16.0	3.0
HVPSs	N/R	1.5	N/R
TOTAL	12.5	56.2	61.9
ALLOCATION	23.2	N/A	N/A
MARGIN	10.7	N/A	N/A
N/R: Not required, N/A: not applicable			

The optical performance of the telescope is strongly influenced by both the uniformity of temperature within M1 and M2 and the temperature profile along the metering struts. Design of the defocus compensation device (athermal spacer) is affected by the difference between the average temperatures of the mirrors and the metering struts. The athermal spacer is sandwiched between the M2 hub and the spider support, and heating M2 causes the athermal spacer to expand, thus changing the distance between M1 and M2 and consequently the focus of the telescope. Although heating the athermal spacer via heaters placed on the shield and hub is not most efficient, configuration of the M2 assembly precludes placing a heater directly on the athermal spacer.

The non-operating modes include decontamination and survival conditions. The telescope must be decontaminated occasionally to maintain the cleanliness of the optics, particularly M1 and M2. In this mode the DPU remains operating, while all other equipment are powered off. Decontamination heaters are sized to raise M1 and M2 to about 50°C. The power dissipation of DPU keeps most of the equipment except the FEE inside the instrument compartment above their lower non-operating AFT limits. Therefore, a replacement heater is applied to the FEE. Based on an extensive amount of thermal analyses, the required operational heater power is lowest when heaters are applied to both the shields and hubs of M1 and M2.

In the survival mode, thermostat-controlled heaters are used to maintain all equipment above their non-operating AFT limits, because all equipment is powered off. All survival heaters except that on the FEE are controlled by thermostats located on the DPU chassis. A separate set of thermostats mounted on the FEE chassis is used to control the survival heaters on FEE, because these heaters also serve as replacement heater in the decontamination mode. Thermostats on the DPU chassis control the survival heaters on the M1 shield, M2 shield and hub, DPU, HVPS, NUV and FUV detectors, and the Grism and Imaging window thermal shields.

A separate set of thermostats controls the M1 and M2 survival heaters that are powered by a different survival bus.

CONCLUSION

A thermal control design that meets both temperature and heater power requirements for all operating and non-operating modes has been developed for the GALEX instrument. The thermal design was developed based on consideration of extreme environments and orbit attitudes consistent with mission constraints. A detailed thermal model of GALEX was developed for performing design trade studies. Extensive thermal analyses were performed to develop specifications for the surface finishes, MLI, and radiators, thermostats, and heaters. The thermal design utilizes operational and survival heaters for the optical and electronic equipment. Replacement heaters are needed by all electronic equipment in the survival mode. Three sets of thermostats are used to control the survival heaters. Each set consists of two thermostats wired in parallel for added reliability. Three sets of thermostats control the following heater strings: (1) M1 and M2 survival heaters; (2) DPU, HVPS, FUV and NUV detectors, Grism, and Imaging window; and (3) FEE. The thermostats for the heaters on M1, M2, and DPU are mounted on the DPU chassis, and the FEE thermostats are located on the FEE chassis. The GALEX thermal design will be validated by the thermal balance test to be conducted in October 2000.

ACKNOWLEDGEMENTS

The authors are indebted to several individuals who contributed to the development of the GALEX instrument thermal design. Henry Awaya, Ray Becker, Ray Garcia, and Jim Stultz composed the thermal peer review board and offered many useful suggestions. C.J. Lee conducted the detailed thermal analysis. Patrick Wu is currently leading the thermal design implementation. Wes Schmitigal oversaw the entire mechanical systems effort. The entire instrument management team, Jim Fanson, Chris Martin, Peter Friedman, David Schiminovich, Amit Sen, and Frank Surber provided meaningful guidance throughout the development phase. We would also like to recognize the rest of the Jet Propulsion Laboratory, the California Institute of Technology, Lightworks Optics, Inc., and Orbital Sciences Corporation team for their support of this effort.

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute of imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

REFERENCES

1. Behee, R. "SINDA3D User's Manual," Version 4.0, Network Analysis, Inc., Tempe, AZ, 1999.

2. Anonymous. "User Manual, Thermal Synthesizer System, Release 7.0.1," LMSMSS-31078, Revision C, NASA Lyndon B. Johnson Space Center, Houston, Texas, 1996.